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Spot the Difference: Operational Event Sequence Diagrams as a Formal Method for Work Allocation in the Development of Single Pilot Operations for Commercial Aircraft

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ABSTRACT

Function Allocation methods are important for the appropriate allocation of tasks between humans and automated systems. It is proposed that Operational Event Sequence Diagrams (OESDs) provide a simple yet rigorous basis upon which allocation of work can be assessed. This is illustrated with respect

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to a design concept for a passenger aircraft flown by just a single pilot where the objective is to replace or supplement functions normally undertaken by the second pilot with advanced automation. A scenario based analysis (take off) was used in which there would normally be considerable demands and interactions with the second pilot. The OESD analyses indicate those tasks that would be suitable for allocation to automated assistance on the flight deck and those tasks that are now redundant in this new configuration (something that other formal Function Allocation approaches cannot identify). Furthermore OESDs are demonstrated to be an easy to apply and flexible approach to the allocation of function in prospective systems.

PRACTITIONER SUMMARY

Operational Event Sequence Diagrams provide a simple yet rigorous basis upon which allocation of work can be assessed. The technique can deal with the flexible, dynamic allocation of work and the deletion of functions no longer required. This is illustrated using a novel design concept for a single-crew commercial aircraft.

INTRODUCTION

Function Allocation is the formal method by which a particular process is allocated either to a human operator, some aspect of automated assistance or a mixture of both. Function (or task) allocation requires consideration of a range of factors. It is also rarely a simple decision to allocate a certain task to either the person or the machine. There is usually some distribution of work and the ultimate decision may be based on considerations such as error rates, workload, cost, technical feasibility and/or legal and ethical issues. While technically functions are a higher level of abstraction than tasks (functions are device independent – see Cook & Corbridge, 1997) the terms tend to be used interchangeably. Deardon, Harrison & Wright (2000) suggested that functions should refer to activities undertaken by whole human-machine systems, whereas tasks refer to a specific activity involving an operator. Furthermore, allocation of function is usually based upon some analysis of lower-level tasks. They suggested the generic term should be allocation of work (the preferred term for the research undertaken in this paper). It is proposed that Operational Event Sequence Diagrams (OESDs) – also sometimes referred to as ESDs (Event Sequence Diagrams) or OSDs (Operational Sequence Diagrams) can provide a basis upon which allocation of work can be assessed. It is argued that OESDs can provide a simple yet rigorous basis for comparison between alternative human/machine configurations of a new system. This is illustrated with reference to the allocation of work and the identification of new requirements for automated assistance in a revolutionary design proposal for a new commercial aircraft.

From a merely technical perspective Bye, Hollnagel & Brendeford (1999) suggested three basic approaches to the allocation of function (the term used in their paper). The 'left-over principle' was simply where the operator's tasks were those that had not or could not be automated. The 'compensatory principle' was arguably a more scientific approach based upon the relative strengths and weaknesses of machines (so called MABA-MABA lists; Men Are Better At – Machines Are Better At – see Fitts, 1951). The 'complementarity principle' (from Grote, Weik, Wäfler & Zölch, 1995) allocated functions based upon the operator's requirement to maintain control and to support the retaining these skills. Bye, Hollnagel & Brendeford (1999) suggested that Function Allocation could be undertaken based upon a Goals-Means Task Analysis (Goals were what need to be achieved – a required system state; Tasks were methods by which it was achieved). The means by which a goal may be achieved may depend upon the control model at the time (strategic; tactical; opportunistic or scrambled: Hollnagel, 1995). The method proposed by Bye, Hollnagel & Brendeford (1999) requires representation of system, operator and control modes in a computer model and is not really suitable at conceptual design stages where something simpler and easier to use is necessary. Authors such as Fuld (2000), however have been particularly critical about Function Allocation approaches based simply upon the principles inherent in Fitts' lists. He argues that this approach is limited and over-simplistic in socio-technical systems. However, the work of Fitts has recently been re-appraised in a modern context and it is argued that the principles derived over 60 years ago still form the basis of a comprehensive, scientifically robust approach to the allocation of function (de Winter & Dodou, 2014).

Most approaches to Function Allocation require a decomposition and analysis of tasks (for example, see the review by Older, Waterson & Clegg, 1997). The results of the task de-composition are then subject to analysis against a number of more widely-based allocation criteria (e.g. task criticality; environmental constraints; workload, feasibility) in addition to human and machine adaptability (see also Jenkins, Stanton, Walker, Salmon & Young, 2008; Grote, Weyer & Stanton, 2014). Most of the Function Allocation techniques evaluated by these authors were rated as being particularly poor when addressing allocations between humans in different roles and in the dynamic allocation of tasks, a criterion which evaluated the ability of a technique to make the best, most flexible use of human/automated resources in a system (especially in unpredictable circumstances). Furthermore, most techniques required considerable analyst training (Stanton, Salmon, Rafferty, Walker, Baber & Jenkins, 2013). Organisationally-rooted criteria for allocation were considered more recently by Challenger, Clegg & Shepherd (2013). This work extended the issue of Function Allocation beyond being merely a technical consideration to the wider, socio-technical system. What is evidently required is a simple way of illustrating who is doing what and when.

However, one of the drawback of all methods reviewed was that they could only compare between various options for the allocations of tasks; identifying new requirements and even the deletion of functions no longer required in certain system configurations was not considered. These issues are important as Function Allocation alone is limited in its scope and utility. Automation changes the nature of work and provides the opportunity to undertake work in a different way, rather than simply replacing human tasks with its automated counterparts (Dekker & Wright, 1997; Dekker & Woods, 2002). Ideally, any method to examine the allocation of function should encompass this issue.

Other approaches to the distribution of tasks and functions between operators and machines has centre upon less technical issues, such as trust (e.g. Lee & Moray, 1992). However since these papers were first published automation has become ever more pervasive and reliable. While trust is still an issue it is no longer a fundamental driver in the allocation of function. Furthermore, the discussion of manual versus automatic control of modern commercial aircraft is now a moot point. There is no such thing as manual control; the only real question is the degree and nature of the automation to be employed at a particular point in flight. More recently an ethical dimension to Function Allocation has been discussed, especially in the case of automated weapons release (Hancock, 2013).

In the aeronautical domain recent work has reverted back to Function Allocation based upon Fitts' lists (Zhang, Tang & Zhang, 2011) although now using computer algorithms. However, to a large extent this is still simply allocation of function by substitution; modern automated systems do not simply replace human functions – they also change aspects of the overall nature of work. Any Function Allocation process for future high-technology systems (such as a single crew commercial aircraft) must be able to identify where the work system has also changed and a function is either no longer needed or alternatively a new function is required.

Operational Event Sequence Diagrams (OESDs)

It is proposed that OESDs can provide a simple yet rigorous basis upon which allocation of work can be assessed in the context of the work flow. They can facilitate comparison between alternative human/machine configurations of a new system; detect tasks and functions no longer needed and help to identify new automation requirements. An OESD can be used to illustrate and describe the interactions between operators and artefacts within a system. OESDs were originally developed by Kurke (1961) as a way of representing operator information decision sequences and subsequently as a way to represent complex, multi-person, tasks (Kirwan & Ainsworth, 1992; Sanders & McCormick, 1993) but this has been extended to include human-machine interaction (Stanton, Salmon, Rafferty, Walker, Baber & Jenkins, 2013). The output of an OESD shows the sequence of operational events, including the tasks performed and the interaction between operators and artefacts over time. There are numerous forms of OESDs, ranging from a simple flow diagram representing task order, to more intricate OESDs which account for team interaction and communication, often including a timeline of the scenario under analysis. OESDs are typically used during the design of complex systems, but they can also be constructed for existing systems and scenarios, in order to evaluate task structure and sequence. Stanton, Sorensen & Banks (2011) used this approach for the analysis of tasks in an extant flight deck. In this case, their use been extended to encompass the incorporation of non-human agents (i.e. automation).

The output from an OESD graphically depicts task processes over time using a set of standardised symbols. OESDs are developed from some kind of initial task analysis of the task or process involved. This may be from observation, analysis of standard operating procedures and/or interviews (in the case of an extant system) or from formal analysis of projected task flows (during design stages of a new system). Each task step is them represented as an OESD symbol (e.g. an operation; decision; delay; storage – see table 4). Each agent in the system is then represented as a column (often referred to as a 'swim lane' – see figures 2 and 3). The OESD is based upon a timeline and each event is entered into the diagram in time order, with the symbols (representing tasks) linked by directional arrows. Further details concerning the construction of OESDs can be found in the Method section.

Reduced Crewing

The trend in commercial aircraft flight deck design has been one of progressive 'de-crewing'. Now, aided by ever increasing levels of automated assistance, two pilots accomplish the same tasks once undertaken by a crew of five. Crew costs for smaller commercial aircraft can vary between 15% and 35% of the direct operating costs (Alcock, 2004). Annual accounts from a low-cost operator suggest that even for larger airliners, crew represent nearly 19% of operating costs before fuel (easyJet, 2013). However, to ensure safe operations, at the present time it is not permitted to operate a revenue-earning, passenger carrying aircraft with just a single pilot.

Some aircraft manufacturers and avionics systems suppliers (e.g. Embraer and Honeywell – Keinrath, Vašek & Dorneich, 2010) are developing the technology for single pilot operated airliners. The approach adopted in these cases centres upon the development of much increased levels of automation (for example, Intelligent Knowledge-Based Systems and adaptive automation). This approach has been used in the past, particularly in the military domain, but with only mixed success (e.g. the COGnitive cockPIT – COGPIT programme - Bonner, Taylor, Fletcher & Miller, 2000; Taylor, Howells & Watson, 2000; and the Cockpit Assistant Military Aircraft – CAMA programme - Schulte & Stütz, 2001; Stütz & Schulte, 2001). CASSY (the Cockpit ASsistant System) was a civil version of CAMA, developed by the same team (see Onken, 1994; Onken, 1997). Reducing the flight deck crew to just a single pilot requires increased assistance, hence the emphasis on the appropriate allocation of work between the human and the aircraft which is essential for safe and efficient flight.

Deutch & Pew (2005) used a cognitive work analysis based approach for developing concepts for single pilot operations which was also predicated upon the notion of incorporating extensive automated assistance into the cockpit. Similar approaches are being used in other programmes, for example the development of an Electronic Standby Pilot (ESP) as part of the Advanced Cockpit for the Reduction of Stress and Workload (ACROSS) project (see http://www.across-fp7.eu/). This project is also concerned with reducing the number of flight deck crew but only in the in the cruise phase of long-haul flights (to permit crew rest and help prevent fatigue).

An alternative design approach for a single crew aircraft to using a large amount of on-board, computing was proposed by Harris (2007). This concept, used a socio-technical systems-based design philosophy utilising a great deal of extant technology. In this case the control and crewing of the aircraft was distributed in real time across both the flight deck and ground stations (see also Stanton, Harris & Starr, 2014). The second pilot was not *replaced* by high levels of automation; they were *displaced*. The design scenario described in this paper is based upon this concept. The use of OESDs for Function Allocation is intended to aid in the identification of appropriate automated assistance to the single pilot.

Reducing the number of flight crew requires a systematic approach to the allocation of work between the pilot and the aircraft, bearing in mind that such an allocation of tasks will change flexibly with regard to circumstance and flight phase. The principle arguments put forward by the airworthiness authorities for two members of flight deck crew has revolved around issues of workload (specifically instances of workload peaks); the reduction of error and pilot incapacitation. However, reducing the number of pilots on the flight deck does not simply require that the function of the other pilot is *replaced* by the automation, what Dekker & Woods (2002) have labelled 'Function Allocation by substitution'. Eliminating one of the pilots also changes the nature of the work undertaken on the flight deck. For example the requirement to coordinate crew, cooperate and communicate on the flight deck itself has workload associated with it which is eradicated on the single crew flight deck. It can be argued that the other second pilot introduces an error mode. Any communication opens up the possibility of mis-communication. Poor Crew Resource Management has been implicated as a contributory factor in nearly 23% of all fatal commercial jet aircraft accidents (CAA, 2008). The effectiveness of the second crew member as an 'error checker' is also questionable. The same CAA statistics show that omission of action or inappropriate action was involved in 39% of accidents; incorrect application of procedures (or deliberate non-adherence to procedures) was implicated in a further 13%. Becoming 'low and slow' (a failure to cross monitor the flying pilot) was a factor in 12% of accidents and a failure to cross check the position of the aircraft was identified as a causal feature in 27% of cases. Observational data obtained during Line Operations Safety Audit flights reported that 47.2% of errors committed by Captains involved intentional non-compliance with Standard Operating Procedures or regulations, and 38.5% were unintentional procedural non-compliance (Thomas, 2003). Thomas also reported that observations of crews during line operations did not demonstrate effective error detection. More than 50% of errors remained undetected by one or both of the pilots. As a result it can be argued that removing one of the crew on the flight deck may actually reduce the potential for accidents.

As a result, the approach to Function Allocation for the single crew flight deck must not only allocate extant tasks appropriately between the pilot and their automated systems, it must also identify those tasks and functions that *are not* required and any new functions that are required. It is not simply about task substitution, an approach implicit in current methods for Function Allocation.

Design Approach

This design concept uses an alternative approach to that of utilising a large amount of on-board, computing (e.g. that using agent-based software) which is difficult to verify and certificate. The proposed approach regards a single crew aircraft as just one part of a wider operating system (Harris & Stanton, 2010). The initial high-level design architecture proposed for operating the Single Crew Aircraft consists of several discrete elements (Stanton, Harris and Starr, 2014). These include the aircraft itself (including pilot) and a ground-based component including the 'second pilot' support station/office; real-time engineering support and navigation/flight planning support. It also uses a great deal of proven extant technology. In this case the control and crewing of the aircraft is distributed in real time across both the aircraft's flight deck and ground stations (see Harris, 2007). The second pilot is not *replaced* by on-board Artificial Intelligence or Intelligent Knowledge-Based Systems, which would be both difficult to develop and challenging to certificate; they are merely *displaced*. This is described diagrammatically in figure 1.

INSERT FIGURE 1 ABOUT HERE

In many ways the aircraft component will be little different to current types. The requirements are that aircraft should be able to function in all types of airspace without any special ATC/ATM procedures and should be able to be flown by air transport licence qualified professional pilots without extraordinary training. It should exhibit an equivalent level of safety to fourth-generation modern airliners (e.g. Boeing 777 or Airbus A330/340 series). Initially such an aircraft will be optimised for shorter-range, low cost operations (including cargo operations) and for ‘thinner’ (low volume) routes where cost of operation is a critical factor. Emphasis will be placed upon reduction of pilot workload and error by simplification of operation.

The ground-based component’s primary function is to support the pilot (e.g. in navigation, system management, air traffic control/management support or fault diagnosis) not necessarily to duplicate their skills and functions. In the case of the single crew aircraft, control from a ground station would only be required in the advent of pilot incapacitation, although assistance from the ground may be required in other circumstances (e.g. during high workload situations or abnormal flight circumstances).

METHOD

OESD Method

In the analyses that follow the OESD method was adapted slightly to accommodate parallel, simultaneous tasks undertaken by two actors (as commonly found on many flight decks) and also to encompass communication aspects. The method employed utilised a scenario-based analysis approach for allocation of work, as advocated by Deardon, Harrison & Wright (2000). Furthermore, rather than being just a simple ‘top-down’ allocation of function approach, OESDs also offered a bottom up perspective, as required when describing design options for socio-technical systems (Jenkins, Stanton, Salmon and Walker, 2011).

To construct an OESD, an analysis of the task sequence was required together with and understanding of how each operation was performed and by whom (or what). The role of artefacts and the interaction of operators with each other and those artefacts was also needed. Stanton, Salmon, Walker, Baber & Jenkins (2013) stated that any task information should include at least the following information:

- Operations or actions
- Transmission of information
- Receipt of information
- Operator decisions
- Storage of information or objects
- Delays or periods of inactivity
- Inspections or checks
- Transportation of data, artefacts and material
- Timeline or task sequence

After this point the OESD could be constructed. This included a timeline with each event depicted in order and entered into the diagram within the appropriate column assigning a task to a particular operator or artefact. In this case the OESD method was adapted and extended to accommodate parallel, simultaneous tasks undertaken by several actors and to encompass communication aspects. A sample of OESD symbology is included in table 4.

Communication plays a vital role in all aircraft operations, hence in the following analyses the symbols in table 4 were supplemented with a further symbol (a speech bubble) indicating communication and the nature of the content of that communication, and a parallelogram indicating the receipt of information.

Flight Scenario

Several critical failure points for single pilot operations were identified for development into scenarios for subsequent analysis (e.g. In-flight depressurisation, followed by emergency descent; pre-take-off checks and all phases of descent, approach and landing – see Harris and Stanton, 2010). However of these only one segment of the larger take-off task is considered in this paper as the emphasis is on illustrating the use of OESDs for Function Allocation.

Take-off is a relatively straightforward task, yet is high workload and has several decision points within it requiring almost immediate choices to be made (in certain non-normal circumstances), hence it is a challenging scenario for single pilot operations. Furthermore, regulations require that all take-offs should be conducted under the manual control of the pilot, hence in the instances considered in this paper this is a mandatory allocation of function. While it is technically possible to perform a completely automated take-off, as a result of these regulatory requirements the pilot can only be supported by the automation in this task. After completion of the take-off task control may be handed over partially or fully to the automation, depending upon circumstances or the pilot's choice. For the purposes of analysis, in this case take-off includes tasks in the pre-take-off briefing up until the end of the acceleration phase (after take-off), where post-take-off checks are completed.

In the following analyses the terms 'Pilot Flying' – PF and 'Pilot Monitoring' – PM are used. Any commercial aircraft with two (or more) crew on the flight deck must be commanded by an appropriately qualified pilot with the rank of Captain, supported by a First Officer (or co-pilot). However, before a flight sector the commander will allocate one pilot to take direct responsibility for handling the aircraft. This pilot becomes PF; the other pilot is designated PM (also sometimes called PNF - 'Pilot Not Flying'). Their role of the latter is to monitor the management of the flight; the PF's control actions and undertake support duties, for example communications and check-list reading. PF and PM duties may be undertaken from either side of the conventional two-crew flight deck.

Material for undertaking the OESD analyses was drawn from a number of sources, including aircraft operations manuals and Standard Operating Procedures (SOPs). These were complemented by a structured de-brief of an experienced, qualified Test Pilot who was type rated on a number of Airbus aircraft and who also helped to devise the various flight scenarios used.

ANALYSIS

Task Sequence Analysis

To construct the OESDs the description of the task sequences (for each pilot) just prior to take-off and ending with the completion of the post take-off checks was undertaken. This was done for just the baseline, two-crew aircraft. These task sequences are presented in tables 1-3.

In the following tables 'check' requires verification of status or values; 'set' signifies setting a value for a parameter; 'receive' indicates the reception of data/information; 'confirm' indicates that information/data has been received and understood; 'advise' indicates an advisory announcement.

INSERT TABLES 1, 2 and 3 ABOUT HERE

OESD Analyses

From the initial de-composition of tasks undertaken during take-off, OESDs were developed to reflect both the allocation of function in the baseline (two crew) aircraft and the proposed allocation of tasks in the single crew version. These are presented in figures 2 and 3. For the sake of simplicity in these initial analyses, only four actors have initially been designated; the two pilots (PF and PM); the aircraft (which includes all aspects of automated assistance) and Air Traffic Control (ATC). Basic flight path control tasks by PF are not represented.

INSERT FIGURES 2 and 3 ABOUT HERE

INSERT TABLE 4 ABOUT HERE

From table 4 it can be seen that the majority of tasks no longer required in a single crew operation involved communication. The remaining work was required to be undertaken by either the remaining pilot or subsumed by the automation. The tasks deleted in the single crew configuration were approximately distributed evenly throughout the sub-phases of take off with the exception of the acceleration phase (see table 5).

INSERT TABLE 5 ABOUT HERE

DISCUSSION

The analysis using OESDs of the take-off flight scenario begins to identify both the key automation components that need further development for a single crew aircraft and provides information concerning the potential allocation of remaining task between pilot and machine, once the second crew member has been removed. The OESD analyses in figures 2 and 3 indicate that the majority of the tasks that the pilot (PF) of a single crew aircraft needs to undertake in the absence of a second pilot (PM) fall into the categories of checking and manual selection.

Checking tasks (in rectangles) where target values fall within well-defined parameters, for example brake temperatures, are easily undertaken by automation, with a simple caution or warning output. Checking of key speeds during the take-off run could also be performed automatically. These are also one of the categories of task identified by Fitts (1951) that 'Machines Are Better At'. The majority of these checking tasks that would previously have been undertaken PM were also associated with a communication task (verifying or informing the PM of system status or a target value). Outputs from the aircraft automation would be best provided via the auditory channel (for example a direct voice output system) to enable the PF to remain 'head up and eyeballs out' during the take-off run and immediately afterwards through the initial phase of climb.

Manual selection tasks are represented in trapezoids. The majority of these tasks, which in a single crew aircraft must now be undertaken by the pilot, are required just after take-off (rotation) and in the initial climb. Although the tasks are relatively simple, they must be undertaken when certain criteria have been met (for example when showing a positive rate of climb or when a certain airspeed has been exceeded). Again, these simple conditions for performance are easily instantiated in an automated system. Often, in a two-crew aircraft such actuations would normally be associated with a check item (also performed by the second pilot). Such tasks are ideal for incorporating into automated support for the pilot.

The OESDs demonstrate that a great number of tasks associated with crew coordination are alleviated in the single crew cockpit (see table 5). This is either as a result of displacing it to the earlier, ground-based flight planning phases or eliminating it altogether as a result of enhanced automation. Many of these tasks are communication-related tasks (table 4) providing either an advisory call-out or invoking a cross check. Mis-communication, however, has been implicated in many fatal accidents and a high percentage on in-flight errors observed during line-checks (CAA, 208; Thomas, 2003). Deleting this requirement or allocating this work to the aircraft automation may serve to reduce this source or error. However, during emergency situations further automated assistance is probably not required. What is needed is a flexible procedure for emergency management and problem solving between the air and the ground-based components of the system. Indeed, in the event of a flight deck fire or depressurisation, being able to control the aircraft from the ground may lead to enhanced levels of safety, not reduced levels.

The OESD analysis also helps to describe the envisaged manner of operation of the ground-based pilot support station. During normal operations the development of some already existing automation features may be necessary (e.g. automatic take-off systems; automated flap retraction/extension systems). However, the development of such systems is required as much to reduce the opportunity for error on the new flight deck (as a result of reduced cross checking) as for a reduction in pilot workload.

In the OESDs presented in figures 2 and 3, the required automation facilities for development on the single crew aircraft can be seen to be:

- Automated cross checking of pilot actions against checklist requirements (where possible)
- Automatic flap retraction (after take-off)
- Runway incursion monitor (take-off and landing)
- Automatic take-off system
- Automatic landing gear retraction and extension
- Automatic monitoring and management of brake cooling
- Direct Voice Output System

Many of these systems already currently exist in some form in modern airliners, are utilised in UAVs or are in the late stages of development prior to becoming available.

The greatest challenge for development of the required systems comes in the form of 'as required' items (see tables 1-3). These require a degree of context awareness if they are to be undertaken using automatic systems on the aircraft. This is possible (for example the increasing degree of autonomy inherent in modern uninhabited air vehicles is developing this technology). Nevertheless, it can still be seen that the pilot remains in overall control of the aircraft and is the prime decision maker (one of the central tenets in Fitts' list: Fitts, 1951) and in the philosophy for automation promulgated by major aircraft manufacturers - Kelly, Graeber and Fadden, 1992).

The utilisation of OESDs as a basis for Function Allocation allows some of the major criticisms of other techniques to be addressed, namely the problems in the representation of context and other aspects of the wider socio-technical system (Fuld, 2000; Challenger, Clegg & Shepherd, 2013). The original purpose of OESD analysis was to represent complex, multi-person, tasks (Kurke, 1961: Kirwan & Ainsworth, 1992; Sanders & McCormick, 1993) so as a result the functions in the wider system are easily incorporated through the addition of additional 'swim lanes'. In this case the only context that has been included is that of Air Traffic Control, however other off-aircraft functions could easily be incorporated into the analysis if required. The wider work context is an important factor to include in the allocation of tasks in the aeronautical case, particularly environmental and regulatory constraints. Regulations require that all take-offs should be conducted under the manual control of the pilot, hence in the instances considered in this paper this is a mandatory allocation of function. While it is technically possible to perform a completely automated take-off, as a result of the regulatory requirements the pilot can only be supported by the automation in this task. After completion of the take-off task control may be handed over partially or fully to the automation, depending upon circumstances or the pilot's choice. Such dynamically allocated tasks are based on factors such workload, cognitive support and operational efficiency. Again, it is easy to represent the point at which control is handed over to the automation in the OESD (see figure 2 – 'Autopilot on') and observed the nature of the changes in the pilot's tasks (which become more management and monitoring oriented). It will be noted that the 'swim lane' allocated to aircraft functions now becomes more populated with control tasks.

Furthermore, the use of OESDs for allocation of work on the flight deck draws upon readily available material (in terms of task flows and operating procedures, etc.) so does not require any special de-composition of tasks (see Older, Waterson & Clegg, 1997). Furthermore OESDs do not require a great deal of training on the part of analysts (Stanton, Salmon, Walker, Baber & Jenkins, 2013) which allows for its easy application.

The reliability of the OESD technique is predicated upon the reliability of the task analysis-based material upon which it is based. In the current application, the source material is taken from aircraft flight manuals (supplemented by subject matter expert analysis and comment). As such, the reliability of the task breakdowns and flows represented in the OESDs is likely to be very high. However, there may be greater challenges to the replicability of the method when drawing upon source material taken from task analyses based upon observation and/or interview. Annett (2003) suggests that the reliability and validity of techniques such as Hierarchical Task Analysis (HTA) are not easy to assess. However, Stanton, Young & Harvey (2014) reported that HTA generally achieves an acceptable level of validity but a poor level of reliability. Different analysts with different experience may produce different task analysis solutions for the same task (Stanton, Salmon, Rafferty, Walker, Baber & Jenkins, 2013). Other related analytical techniques, such as link analysis have exhibited high levels of intra-rater and predictive validity, however inter-rater reliability values were not observed to be quite so high (Stanton, Young & Harvey, 2014). As a result, care should therefore be taken upon ensuring the quality of the material upon which the analyses are based.

The use of OESDs for the potential allocation of function is being utilized to examine various potential configurations for the operation of a single crew commercial aircraft. A scenario-based approach is being used (encompassing normal; non-normal and emergency operations). These analyses will serve to define not only the allocation of function between the pilot and aircraft automation, but also between the aircraft and potential ground-based components, further demonstrating the flexibility of this approach.

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Table 1 **Taxi and pre-take-off checks task sequence**

Taxi Checks			
Pilot Flying		**Pilot Monitoring**	
FLIGHT CONTROL	Check		
ALTERNATE			
HEADING	Set		
FLIGHT INSTRUMENTS	Check	FLIGHT INSTRUMENTS	Check
CABIN REPORT	Receive		
TAKE OFF BRIEFING	Confirm		
Before Take Off			
		BRAKE TEMP	Check
		BRAKE FANS	Off
APPROACH PATH	Check	TAKE OFF/LINE UP	
CLEAR OF TRAFFIC		CLEARANCE	Obtain
CABIN CREW	Advise	ENGINE MODE SEL	As Required[2]
		TCAS	Set to TA or TA/RA
EXTERIOR LIGHTS	Set	PACKS 1 + 2	As Required
TAXI CHECKS END			

[2] Conditions for selecting IGN/START prior to takeoff: Runway with standing water or when heavy rain or severe turbulences expected after takeoff

Table 2 Take-off task sequence

Takeoff			
Pilot Flying		**Pilot Monitoring**	
Takeoff Initiation and Power Set			
ANNOUNCE CHRONO BRAKES THRUST LEVERS	'Take Off' Start Release 1) From IDLE to 50 % N1 (1.05 EPR) 2) From Both engines THR stabilized to T/O THR	CHRONO	Start
Takeoff Run			
ANNOUNCE FMA BEFORE 80 kt AT 100 kt ANNOUNCE	 'Checked'	FMA ANNOUNCE N1 EPR ANNOUNCE	Check[3] 'Checked' Check '100 Kts'
Rotation			
Pilot Flying		**Pilot Monitoring**	
  ROTATION When Vertical Speed Positive and RAD ALT Active ORDER ORDER	 Perform 'Gear Up' 'Autopilot On'	At V1 ANNOUNCE At VR ANNOUNCE LANDING GEAR ANNOUNCE GROUND SPOILER EXTERIOR LIGHTS AUTOPILOT	'V1' 'Rotate' Up 'Gear Up' Disarm Set[4] On

[3] FMA Announcements check:
- TOGA or FLEX thrust set
- SRS (Speed Reference System) is active (Limited to V2 + 20 kts)
- RWY - system is picking up an ILS signal for the runway
- Autothrust system armed (expect engage after 1,500 feet)

[4] Set NOSE and RWY TURN OFF lights switches to OFF; LANDING lights should be left ON

Table 3 Post take-off task sequences

Preselected Heading			
Pilot Flying		**Pilot Flying**	
ANNOUNCE FMA If RWY TRK Mode Is[5] Engaged: HEADING	'AP 1 (or AP 2)' Maintain Runway Heading or Select NAV mode	FMA ANNOUNCE	Check 'Checked'
Thrust Reduction			
Pilot Flying		**Pilot Monitoring**	
When LVR CLB Flashing On FMA: THRUST LEVERS	 CL Gate[6]	 If takeoff was performed with air conditioning packs off: PACKS 1 AND 2	 On
Acceleration			
Pilot Flying		**Pilot Monitoring**	
At Acceleration Altitude At F Speed with positive speed trend ORDER At S Speed with positive speed trend ORDER	 'Flaps 1' 'Flaps 0'	 ANNOUNCE FLAPS 1 CONFIRM ANNOUNCE	 'Speed Checked' Select 'Flaps 1' 'Speed Checked' Select 'Flaps 0'
After Takeoff			
		APU BLEED/MASTER SW ENG MODE SEL TCAS	As Required[7] As Required[8] TA/RA[9]

[5] RWY TRK mode keeps the aircraft on the runway track memorised at 30ft Rad Alt

[6] Thrust Reduction Altitude: 1,500 ft AGL is default value in FMS but can be modified, as required.

[7] If APU has been used during takeoff

[8] IGN, in case of severe turbulence or heavy rain

[9] If TA has been used during takeoff

		ANTI ICE	As Required[10]
Transition Altitude			
At Transition Altitude ANNOUNCE BARO REF ALTITUDE ANNOUNCE	 'Pull Standard' Pull knob for 1013 mb Check 'Checked'	 BARO REF ANNOUNCE	 Pull knob for 1013 mb 'Standard Cross 'Checked'
TAKEOFF CHECKS END			

[10] ENGINE ANTI ICE, in case of expected icing conditions

Table 4 A sample of the OESD standardised symbols and total instances of these operations in the current, two-crew (baseline) aircraft configuration and corresponding single pilot operation during take-off (aggregated across figure 1-3).

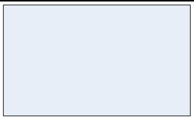
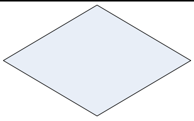
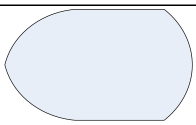
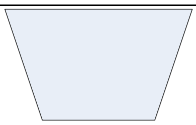
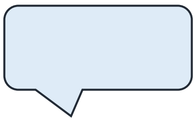
Symbol	Meaning	Current two-crew aircraft configuration	Single Pilot Operation
	Process or Task	12	12
	Decision	3	3
	Display	14	13
	Manual Operation	19	19
	Connector	73	50
	Speech Communication	24	5
	Receive	2	1

Table 5 Total number of operations, broken down by sub-phase of take-off in the current, two-crew (baseline) aircraft configuration and corresponding single pilot operation during take-off.

	For PF and PM only		
	Current, two-crew baseline configuration	**Single Pilot Operation**	**Difference**
Before Taxiing	2	2	0
Taxi Checks	7	5	2
Before Take-Off (TO)	9	9	0
Take-Off Initiation and Power Set	5	4	1
TO Run	6	3	3
Rotation	7	3	4
Pre-Select Heading	11	8	3
Acceleration	12	6	6
After Take-Off	4	4	0
Transition Altitude	6	2	4
TOTAL	**69**	**46**	**23**

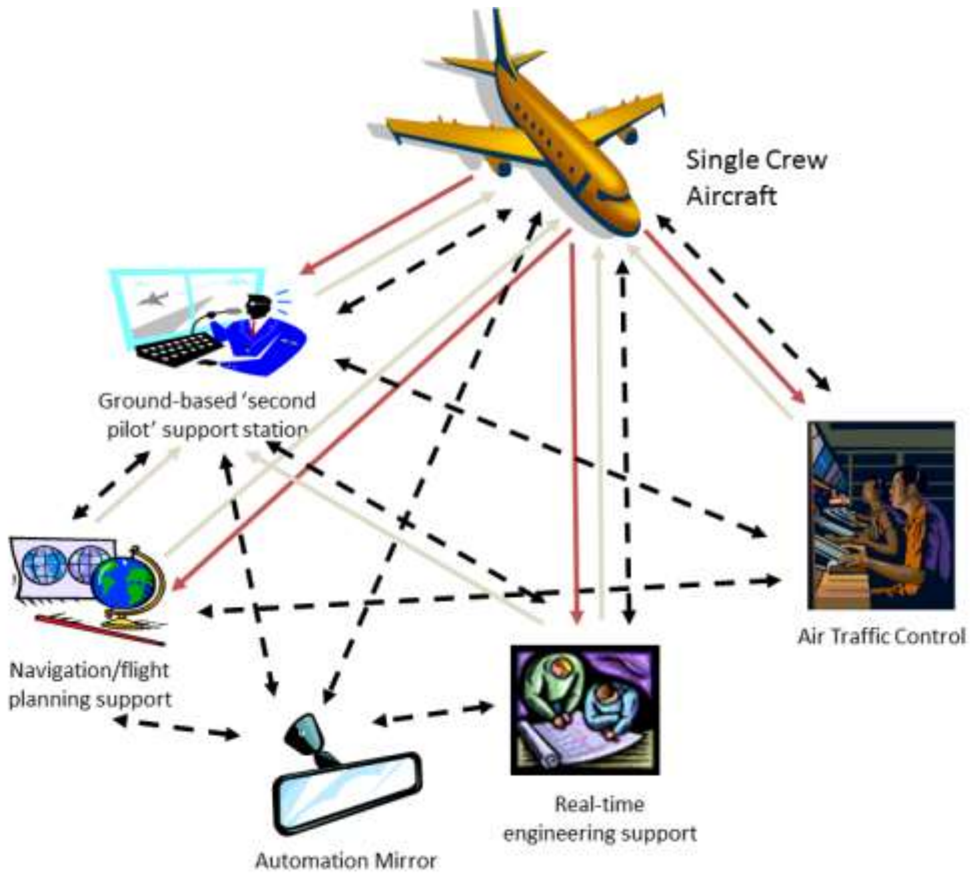
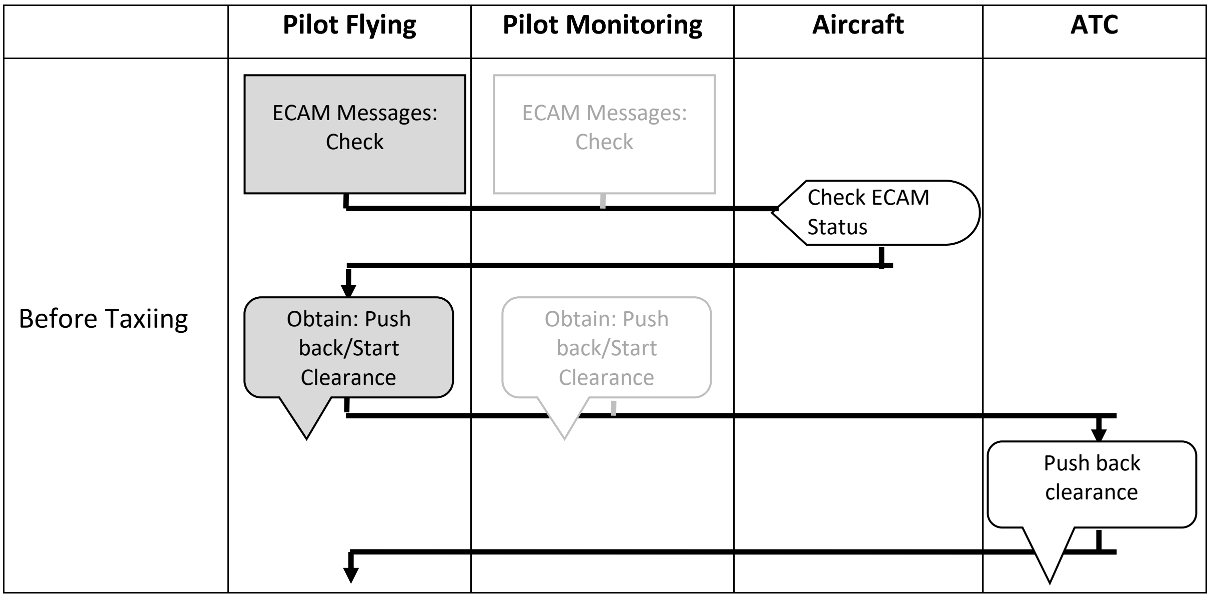
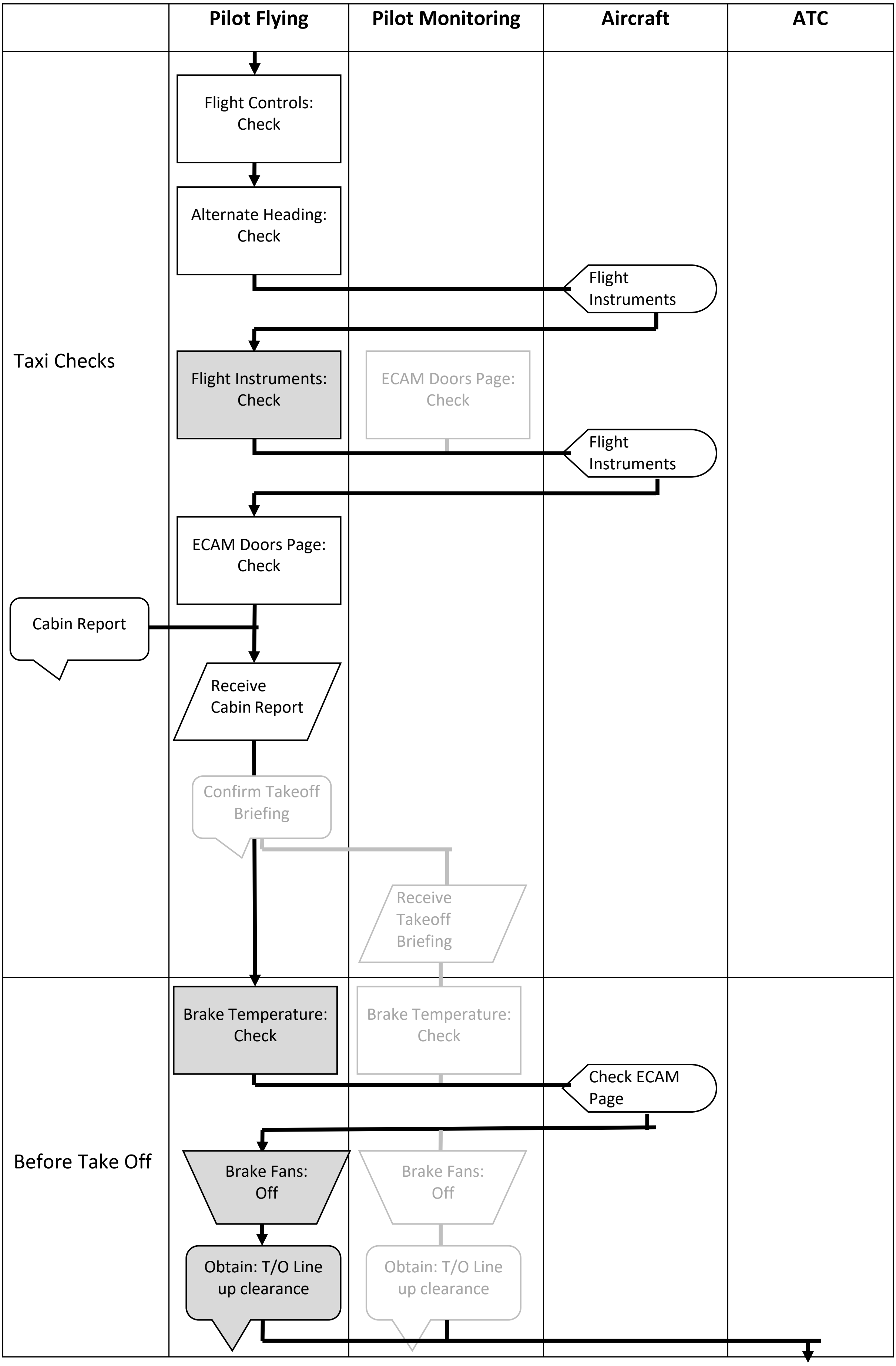

Single Crew
Aircraft
Ground-based 'second
pilot' support station
Navigation/flight
planning support
Air Traffic Control
Real-time
engineering support
Automation Mirror

Figure 2 **Taxi and pre-take-off OESD analyses. Tasks depicted in light grey are now no longer required in a single crew aircraft configured as described earlier. Tasks depicted against a grey background are new tasks that the sole pilot must now undertake or are candidates for new automated assistance.**





Pilot Flying
Pilot Monitoring
Aircraft
ATC
Taxi Checks
Flight Controls: Check
Alternate Heading: Check
Flight Instruments
Flight Instruments: Check
ECAM Doors Page: Check
Flight Instruments
ECAM Doors Page: Check
Cabin Report
Receive Cabin Report
Confirm Takeoff Briefing
Receive Takeoff Briefing
Before Take Off
Brake Temperature: Check
Brake Temperature: Check
Check ECAM Page
Brake Fans: Off
Brake Fans: Off
Obtain: T/O Line up clearance
Obtain: T/O Line up clearance

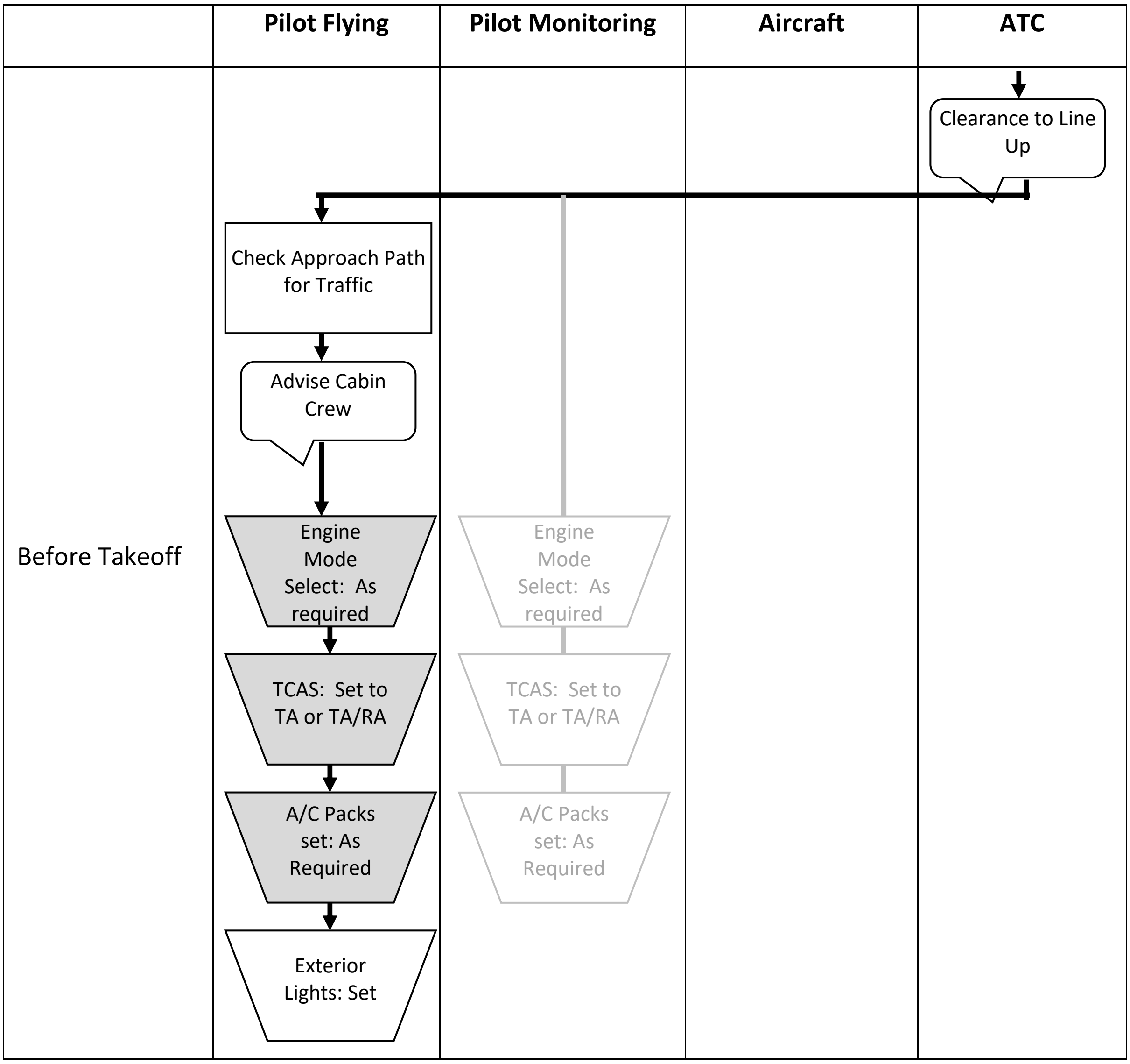
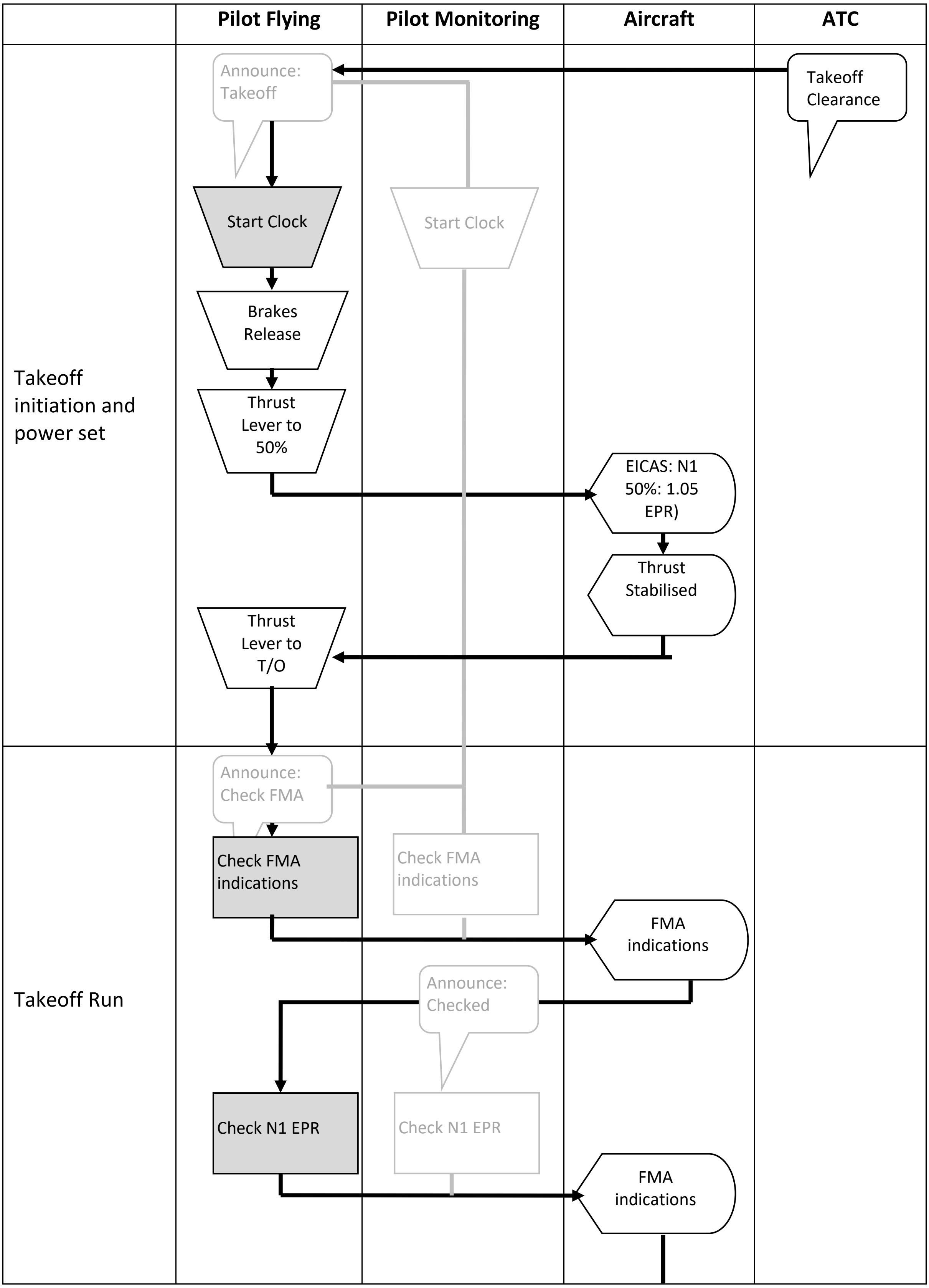
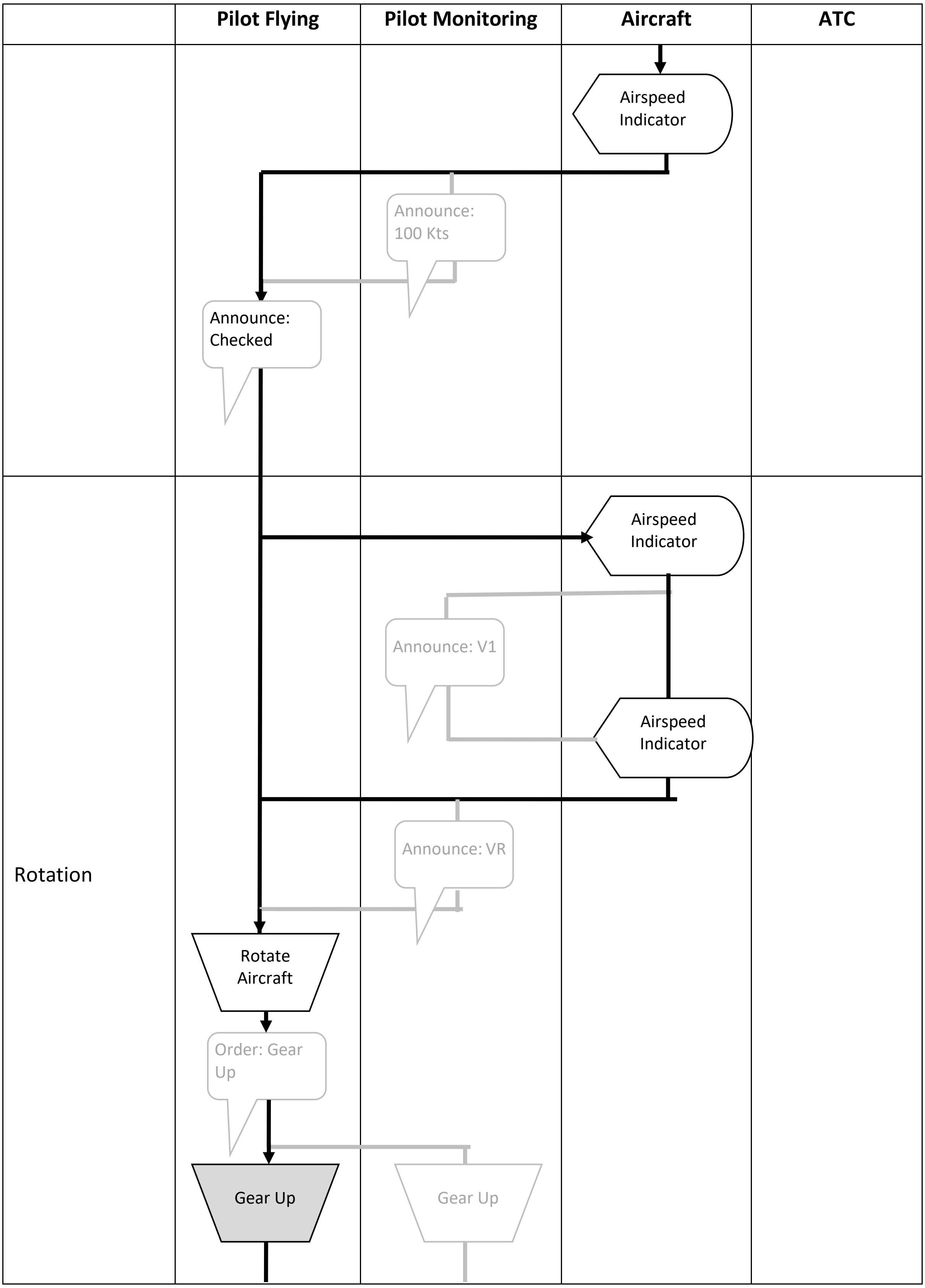
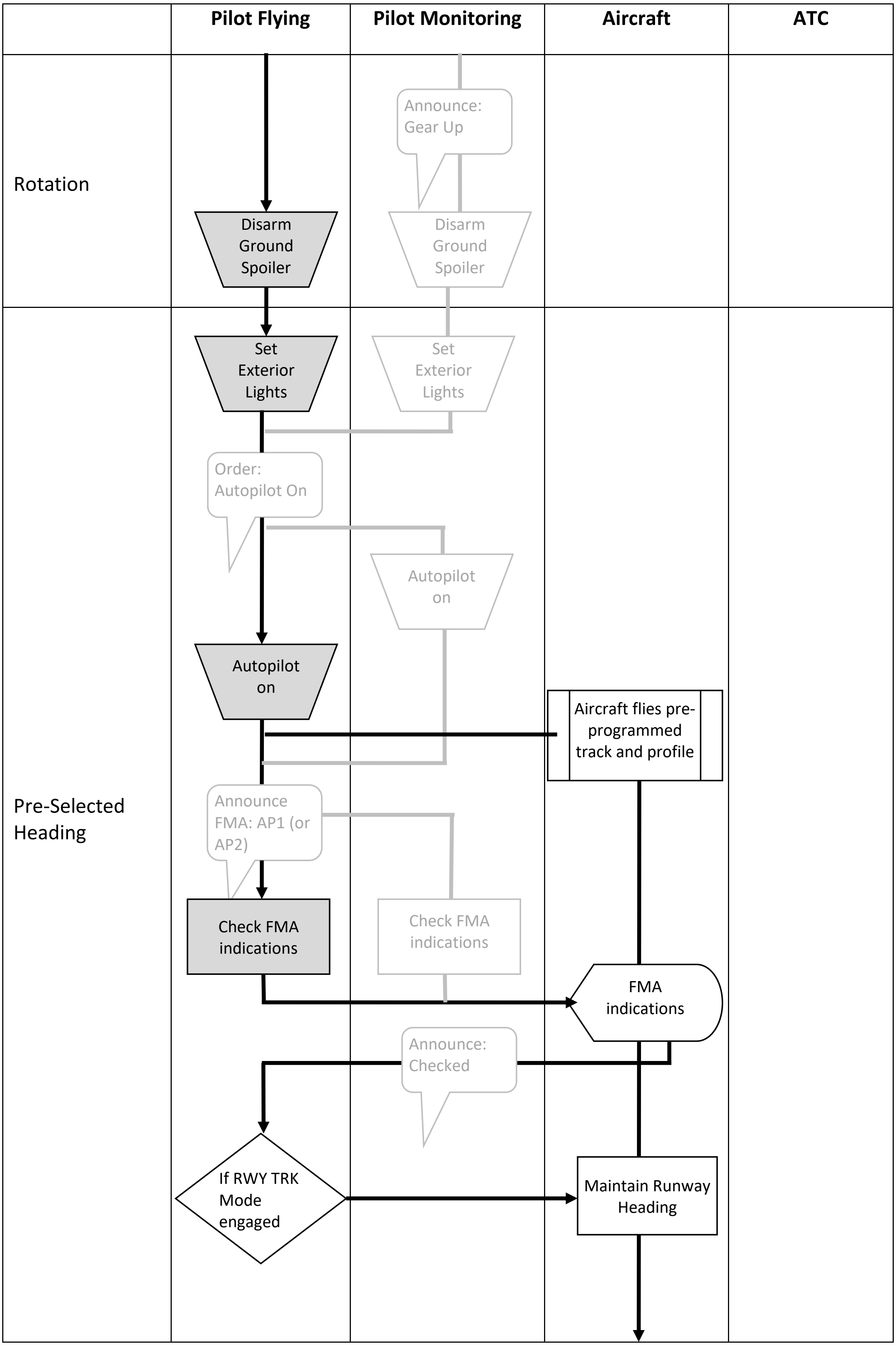

Pilot Flying
Pilot Monitoring
Aircraft
ATC
Before Takeoff
Clearance to Line Up
Check Approach Path for Traffic
Advise Cabin Crew
Engine Mode Select: As required
TCAS: Set to TA or TA/RA
A/C Packs set: As Required
Exterior Lights: Set
Engine Mode Select: As required
TCAS: Set to TA or TA/RA
A/C Packs set: As Required

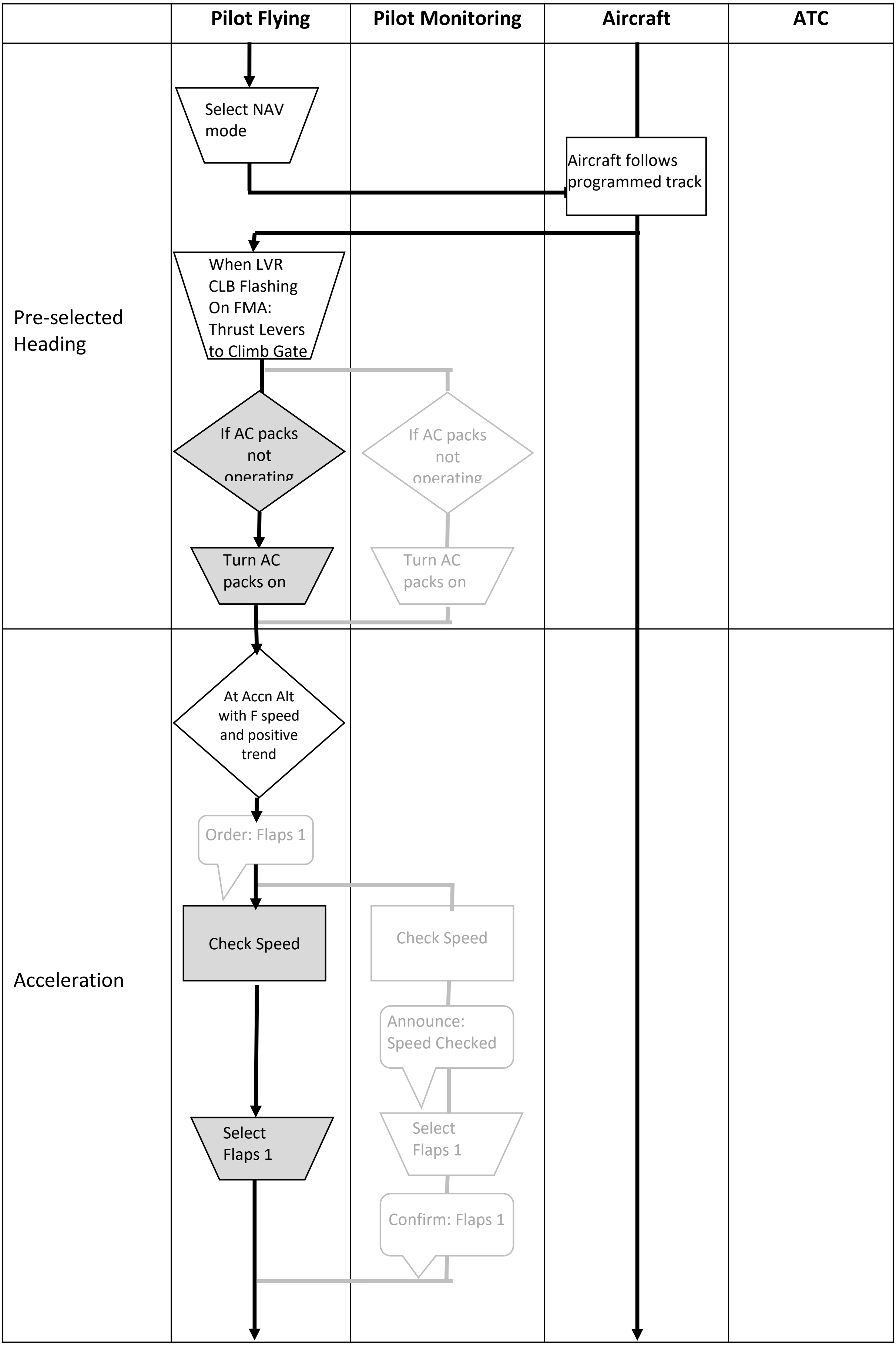
Figure 3 **Take-off and post-take off OESD analyses. Tasks depicted in light grey are now no longer required in a single crew aircraft configured as described earlier. Tasks depicted against a grey background are new tasks that the sole pilot must now undertake or are candidates for new automated assistance.**

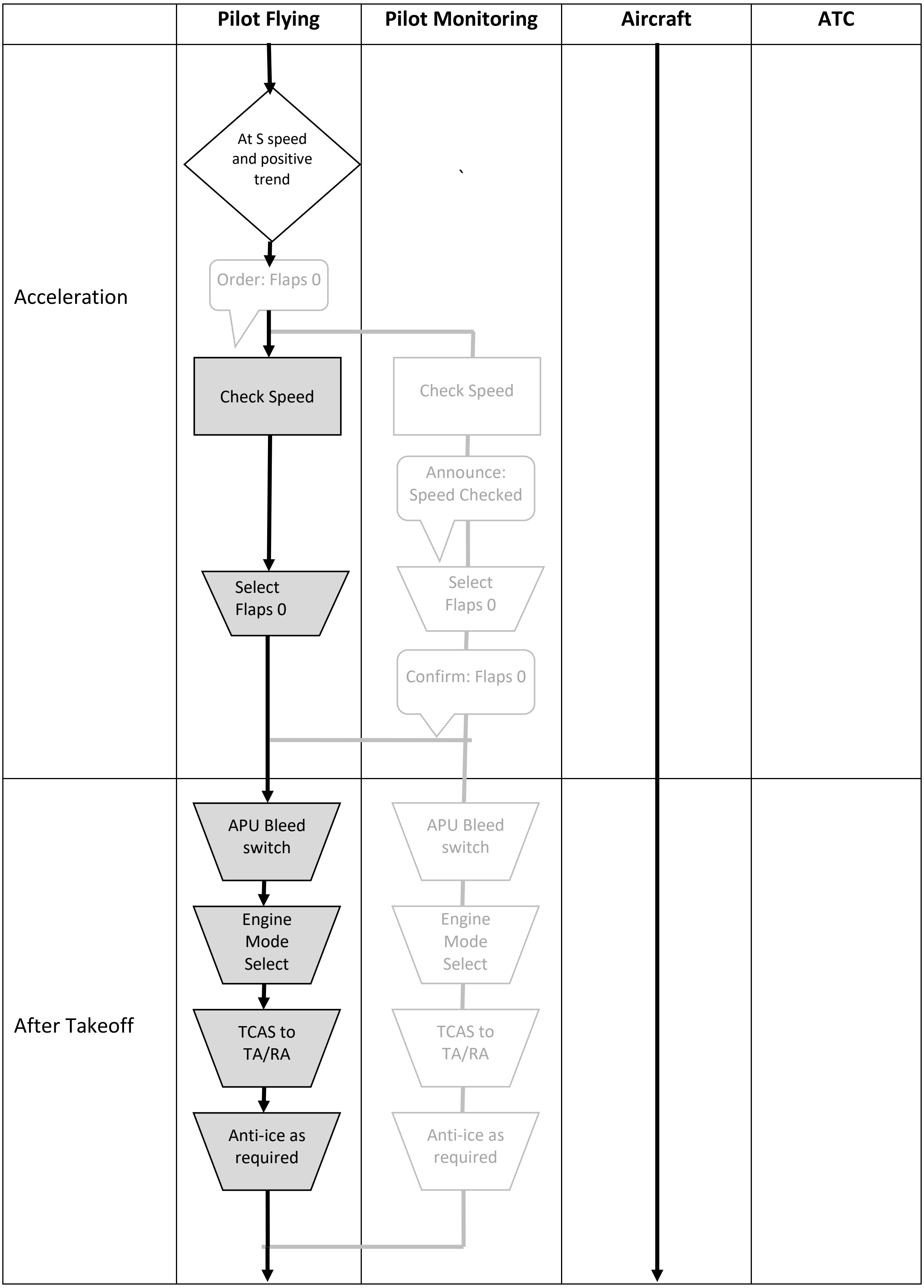


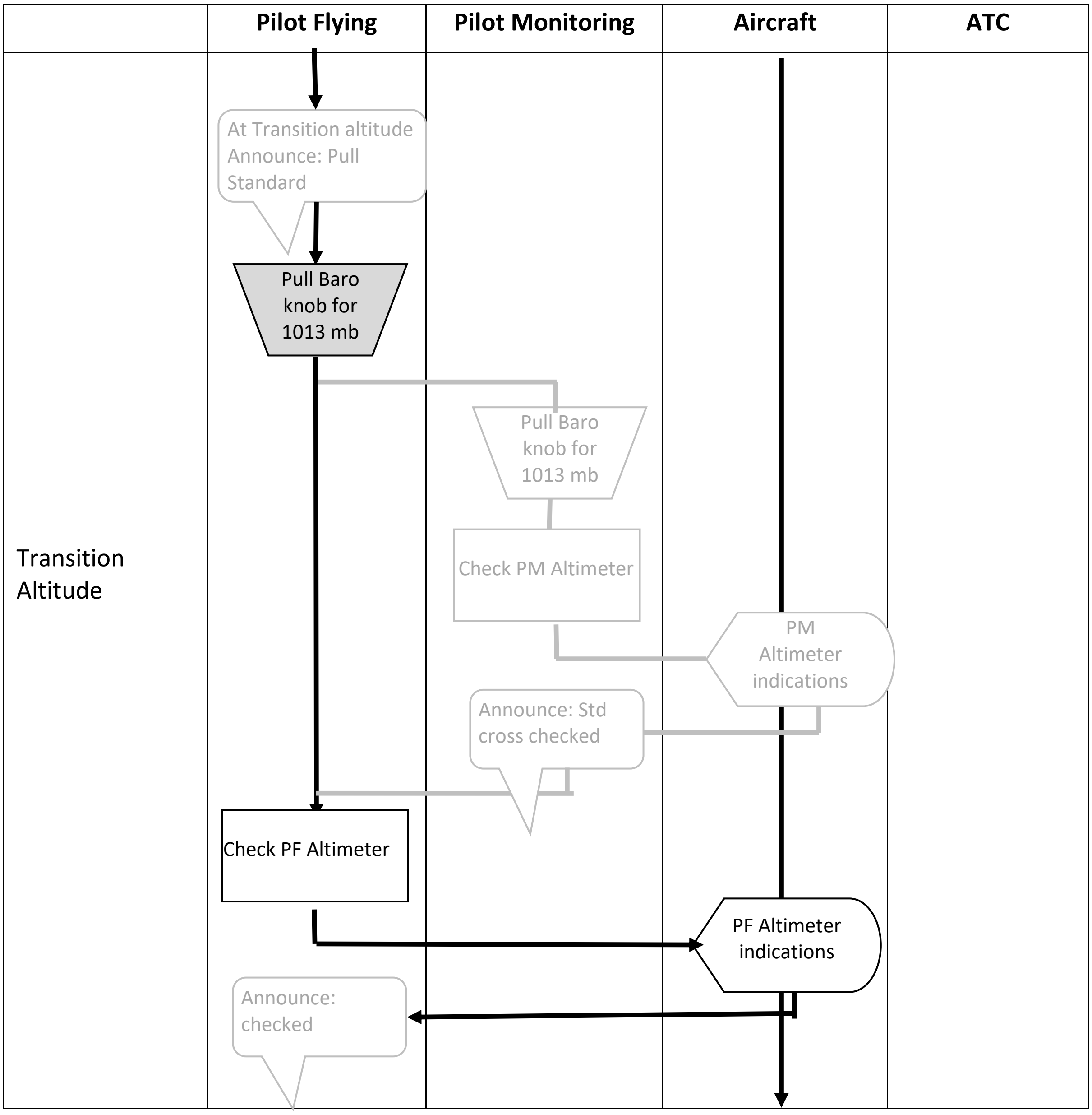


Pilot Flying
Pilot Monitoring
Aircraft
ATC
Airspeed Indicator
Announce: 100 Kts
Announce: Checked
Rotation
Airspeed Indicator
Announce: V1
Airspeed Indicator
Announce: VR
Rotate Aircraft
Order: Gear Up
Gear Up
Gear Up


Pilot Flying
Pilot Monitoring
Aircraft
ATC
Rotation
Announce: Gear Up
Disarm Ground Spoiler
Disarm Ground Spoiler
Pre-Selected Heading
Set Exterior Lights
Set Exterior Lights
Order: Autopilot On
Autopilot on
Autopilot on
Aircraft flies pre-programmed track and profile
Announce FMA: AP1 (or AP2)
Check FMA indications
Check FMA indications
FMA indications
Announce: Checked
If RWY TRK Mode engaged
Maintain Runway Heading


Pilot Flying
Pilot Monitoring
Aircraft
ATC
Pre-selected Heading
Select NAV mode
Aircraft follows programmed track
When LVR CLB Flashing On FMA: Thrust Levers to Climb Gate
If AC packs not operating
If AC packs not operating
Turn AC packs on
Turn AC packs on
Acceleration
At Accn Alt with F speed and positive trend
Order: Flaps 1
Check Speed
Check Speed
Announce: Speed Checked
Select Flaps 1
Select Flaps 1
Confirm: Flaps 1


Pilot Flying
Pilot Monitoring
Aircraft
ATC
Acceleration
At S speed and positive trend
Order: Flaps 0
Check Speed
Check Speed
Announce: Speed Checked
Select Flaps 0
Select Flaps 0
Confirm: Flaps 0
After Takeoff
APU Bleed switch
APU Bleed switch
Engine Mode Select
Engine Mode Select
TCAS to TA/RA
TCAS to TA/RA
Anti-ice as required
Anti-ice as required



Pilot Flying
Pilot Monitoring
Aircraft
ATC
Transition Altitude
At Transition altitude Announce: Pull Standard
Pull Baro knob for 1013 mb
Pull Baro knob for 1013 mb
Check PM Altimeter
PM Altimeter indications
Announce: Std cross checked
Check PF Altimeter
PF Altimeter indications
Announce: checked